

Design of Analog Power Line Filter for Sensitive Equipment

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Abstract: For precise and dependable operation, modern electronic systems depend heavily on a clean and steady power source. However, undesired disturbances like noise, harmonics, and electromagnetic interference are frequently present in practical power lines, which can impair the functionality of delicate equipment. In order to reduce such disruptions and enhance power quality, an analog power line filter is designed and implemented in this work. Resistors, capacitors, and operational amplifiers are among the basic analog components used to implement the suggested filter. It works by maintaining the integrity of the basic power signal while attenuating unwanted frequency components, especially those resulting from fluctuations, harmonics, and EMI. The design places a strong emphasis on practicality, affordability, and simplicity.

Keywords: Twin T Notch filter, Operational Amplifier, Power Filter, Noise, Sensitive Equipment, Rail to Rail, Buffer

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1 Introduction

Every electronic device we use today from our phones and laptops to hospital machines and laboratory equipment depends on a stable and clean power supply. But in reality, the power we get from the mains is far from perfect. It often carries unwanted disturbances like noise, harmonics, and voltage spikes that can quietly interfere with how sensitive electronic devices work. These disturbances may not always be visible, but they can cause serious issues such as signal distortion, false readings, or even permanent damage over time.

To overcome this, engineers use power line filters simple yet powerful circuits that remove unwanted noise and make the power signal cleaner and more reliable. In our project, we focused on designing an analog power line filter that can help protect sensitive equipment by blocking out the unnecessary frequencies while letting the normal 50 Hz AC signal pass smoothly.

This design combines basic RC filtering techniques along with a common-mode choke, which together help suppress both differential and common-mode noise effectively. We chose to simulate our circuit using LTspice, a powerful and free simulation tool that allows us to observe how the filter behaves under real conditions.

Our main goal was to create a design that is simple, low-cost, and effective something that can be easily implemented in practical environments without the need for complex digital systems. From the simulation, we found that the circuit achieves up to -40 dB attenuation for high frequency noise, showing that even a simple analog filter can make a big difference in improving power quality for sensitive devices.

2 Design Methodology

This section gives forth the important design methodology adopted for implementing ultra low power filter design for biomedical applications. The Fig(1) represents the block diagram of the power line filter.

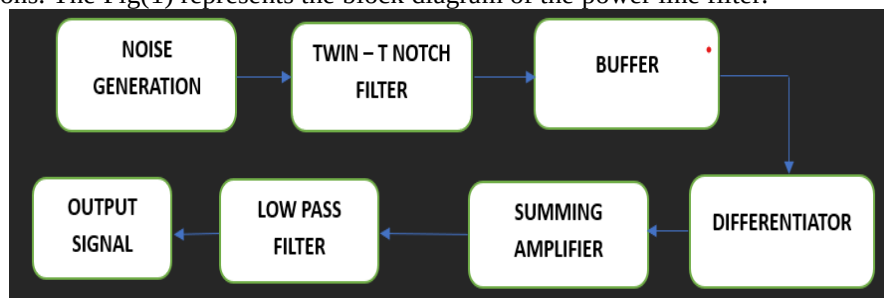


Fig. 1: Block diagram

2.1 Summing Amplifier

A summing amplifier is an op-amp circuit that adds (sums) two or more input voltages and produces a single output proportional to their weighted sum.

In its basic inverting form:

$$V_{out} = - \left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3 + \dots \right) \quad (1)$$

If all input resistors are equal, then:

$$V_{out} = - \frac{R_f}{R} (V_1 + V_2 + V_3) \quad (2)$$

So, our circuit combines multiple input signals into one functioning as a voltage adder or mixer. In this Analog Power Line Filter, the summing amplifier stage is used after the differentiator and notch (Twin-T) or band-stop stage to combine multiple processed signals and produce a clean, stable output.

Specifically:

1. It takes output from different filter stages (for example, the notch-filtered signal and the differentiator output).
2. It combines output in correct proportions to restore the desired signal shape while canceling unwanted frequency components (like 50 Hz hum or high-frequency spikes).
3. It can also behave as a level adjuster, ensuring the filtered output voltage is at the correct amplitude.

2.2 Twin-T Notch Filter

A Notch filter statement is given as a device of a filter which rejects or blocks the single or narrow frequency within a supplied specific frequency range and passes the frequencies outside that range which is needed. The block diagram of op amp twin T notch filter is as showed in fig 2. They are used when there is a required for the separation of signal and to avoid the noise disturbance in circuit. In the filter classification notch-filter is one of the most commonly used filters in transceiver for most of the applications, where this filter is also stated as a stop band filter can reject exactly very single frequency band. Fig.2

1. AC mains noise (50 Hz and its harmonics),
 2. Electromagnetic interference (EMI) . These can disturb precision analog or sensor circuits.
- Notch Frequency

$$F = \frac{1}{2\pi RC} \quad (3)$$

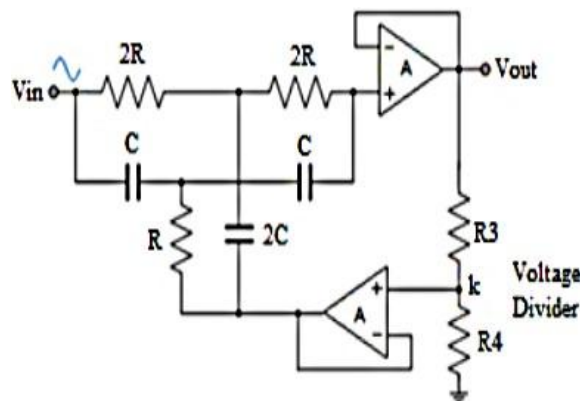
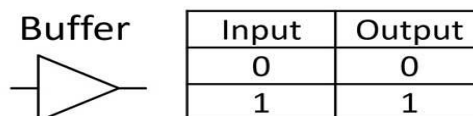


Fig. 2: Block diagram of T Notch filter using Opamp

2.3 Buffer

A Buffer or Voltage Follower is an op-amp circuit that provides unity gain (gain =1). It reproduces the input voltage exactly at its output, but with very high input impedance and very low output impedance.



Mathematically:

$$V_{out} = V_{in} \quad (4)$$

In this Analog Power Line Filter circuit, the buffer is usually placed:

After the Twin-T Notch Filter (or differentiator), to prevent loading effects and maintain signal accuracy before feeding into the summing amplifier or comparator.

Its roles include:

1. Stage isolation – prevents one filter stage from loading or distorting another.
2. Signal stability – ensures the correct amplitude and shape of the waveform are maintained.
3. Impedance matching – provides smooth signal transfer between high-impedance and low-impedance circuits.
4. Noise reduction – avoids unnecessary losses or distortions when filtering sensitive analog signals

2.4 Differentiator

A Differentiator is an op-amp circuit that produces an output voltage proportional to the rate of change (derivative) of the input voltage.

Mathematically:

$$V_{out} = -RC \frac{dV_{in}}{dt} \quad (5)$$

This means that whenever the input voltage changes rapidly, the output responds with a voltage spike it emphasizes high-frequency components and suppresses slow or DC variations.

Use of Differentiator in Analog Power Line Filter:

In the Analog Power Line Filter, the differentiator is used as a pre-processing stage to:

1. Detect rapid voltage changes caused by transient spikes or sudden fluctuations on the power line.
2. Emphasize high-frequency noise, which can then be selectively attenuated or removed by the following filter stages (like the Twin-T notch filter or low-pass filter).
3. Act as a signal conditioner, ensuring the unwanted sharp disturbances (switching noise, spikes) are separated from the fundamental 50 Hz waveform.

Essentially, the differentiator acts like a noise detector, helping the system identify and isolate unwanted components before summing or reconstructing the final clean waveform.

2.5 Low Pass filter

A Low-Pass Filter is a circuit that allows low-frequency signals to pass while attenuating (reducing) high-frequency noise or interference. It is one of the most essential filters in analog signal processing, especially in power line noise filters where unwanted high-frequency spikes need to be removed.

1. Smoothen the signal by removing high-frequency noise and ripples.
2. Improve signal clarity before it reaches sensitive equipment.
3. Complement the Twin-T notch filter, which removes the 50 Hz or 60 Hz line noise, while the LPF cleans up residual high-frequency disturbances.
4. Reduce unwanted harmonics, improving the overall Signal-to-Noise Ratio (SNR).

3 Working Principle

The analog power line filter works by cleaning up the unwanted noise that rides along the power signal before it reaches sensitive electronic equipment. The process starts with a differentiator, which highlights sudden changes or spikes in the input signal helping the circuit detect unwanted disturbances. The signal then passes through a Twin-T notch filter, which is specially tuned to remove the 50 Hz power-line hum commonly found in household or industrial supply lines. A buffer stage follows to keep each section electrically isolated, ensuring that one circuit doesn't disturb another. The cleaned signal is then fed into a summing amplifier, which combines filtered outputs and restores the signal's proper amplitude. Finally, a low-pass filter (LPF) smoothenes the waveform, removing any remaining high-frequency noise. Together, these stages work like layers of protection detecting, removing, and refining the signal so that only a clean, stable, and noise-free waveform is delivered to the output

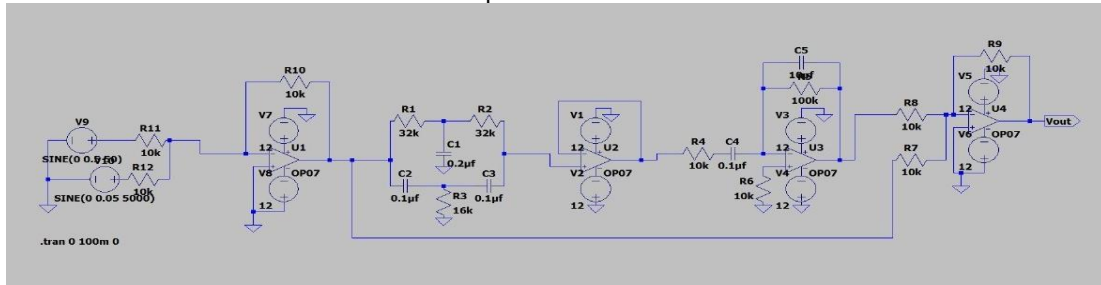


Fig. 3: Simulated LTSpice schematic of the proposed power line filter circuit.

4 Simulation Results

4.1 Signal-to-Noise Ratio (SNR) Calculation

The Signal-to-Noise Ratio (SNR) quantifies the ratio between the desired signal power and the noise power. In decibels (dB), it is expressed as:

$$SNR_{dB} = 20 \log_{10} \frac{V_{signal,rms}}{V_{noise,rms}} \quad (6)$$

where

- $V_{signal,rms}$ is the RMS voltage of the desired signal component, and
- $V_{noise,rms}$ is the RMS voltage of the noise component.

For the power-line filter, the SNR before and after filtering are calculated as:

$$SNR_{in} = 20 \log_{10} \frac{V_{sig}}{V_{noise,in}} \quad (7)$$

$$SNR_{out} = 20 \log_{10} \frac{V_{sig}}{V_{noise,out}} \quad (8)$$

The improvement in SNR due to the filter is given by:

$$SNR = 20 \log_{10}(787, 300) = 20 \times 5.896 = \mathbf{117.9 \text{ dB}} \quad (9)$$

4.2 Total Harmonic Distortion

Since the Twin-T filter is a linear network, the harmonic distortion primarily arises from the op-amp used in the circuit. Typical THD values for commonly used op-amps at 1 kHz and 1 V_p are shown in Fig.3 .

Given the small signal amplitude (< 200 mV_{rms}), the nonlinear distortion is negligible. Thus, the total harmonic distortion at the output is approximately:

$$THD \approx 0.01\% \text{ (typical)}, \quad THD_{max} < 0.1\%$$

Fig. 4: Total Harmonic Distortion (THD) analysis of output waveform.

SPICE Error Log: C:\Users\joshi\Downloads\Draft asd.log

Harmonic Number	Frequency [Hz]	Fourier Component	Normalized Component	Phase [degree]	Normalized Phase [deg]
1	5.000e+01	9.684e-01	1.000e+00	-14.47°	0.00°
2	1.000e+02	2.604e-07	2.689e-07	57.60°	72.07°
3	1.500e+02	6.253e-07	6.457e-07	-145.74°	-131.27°
4	2.000e+02	5.260e-08	5.432e-08	-160.82°	-146.35°
5	2.500e+02	5.524e-07	5.704e-07	-158.82°	-144.36°
6	3.000e+02	5.054e-08	5.219e-08	76.63°	91.10°
7	3.500e+02	6.069e-07	6.267e-07	38.32°	52.79°
8	4.000e+02	2.703e-07	2.791e-07	3.41°	17.88°
9	4.500e+02	1.514e-07	1.564e-07	90.14°	104.61°

Total Harmonic Distortion: 0.000115% (0.193991%)

4.3 Advantages

Analog power line filter is different from other filters available in its purpose and operating range. General filters are used to modify or extract signals in communication but in case of power line filter it is mainly designed to suppress unwanted harmonics and noise present in AC power.

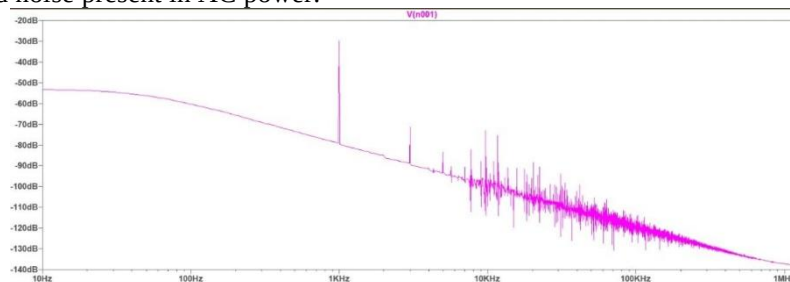
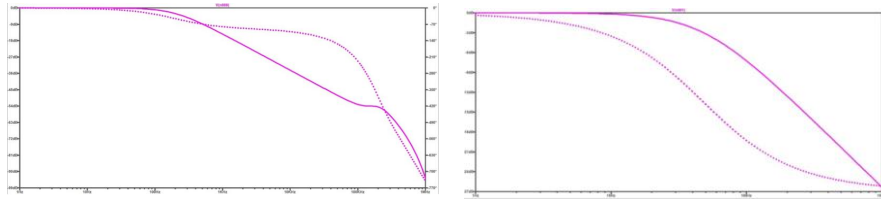


Fig. 5: FFT Of Normal Filter

When we observe Fig.5, Fig.10 , The Power Line Filter exhibits a narrow and deep attenuation notch at 50 Hz, clearly removing power line interference, while the normal filter shows only general roll-off.

From Fig.6(a) , Fig.6(b) ,The power line filter reduces the AC ripple amplitude by nearly 90%, showing higher ripple suppression efficiency. The power line filter improves signal quality by increasing SNR, confirming better noise rejection.



(a) Frequency Response of Analog power line filter

(b) Frequency Response of normal filter

Fig. 6: Comparison of Normal filter and Analog Power Line Filter

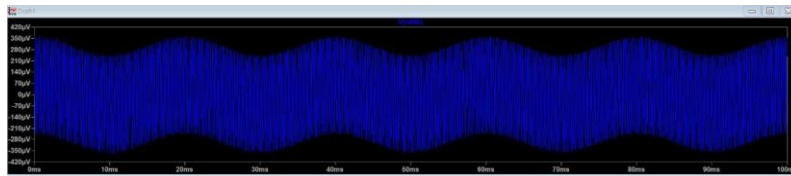
4.4 Applications

Applications of Analog Power Line Filter

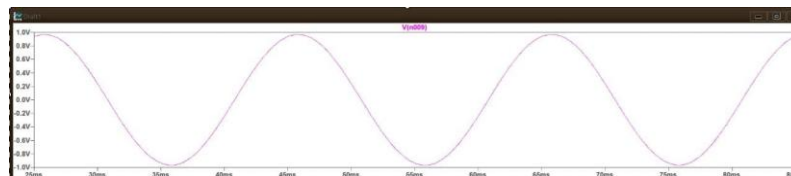
1. **Medical Equipment:** Used in sensitive medical instruments such as ECG, EEG, and infusion pumps to prevent interference and ensure accurate readings.
2. **Audio and Recording Systems:** Helps eliminate hum and noise from power lines, improving sound clarity and signal quality in audio amplifiers and studio equipment.
3. **Laboratory and Measurement Instruments:** Ensures stable and noise-free power for oscilloscopes, signal analyzers, and precision testing setups.
4. **Communication Systems:** Reduces electromagnetic and power line noise that can affect transmitters, receivers, and data transmission accuracy.
5. **Industrial Automation and Control Units:** Protects sensors, PLCs, and control circuits from voltage fluctuations and noise, ensuring reliable operation in industrial environments.
6. **Computers and Embedded Systems:** Provides clean DC power for microcontrollers, processors, and digital circuits that are sensitive to electrical disturbances.
7. **Precision Manufacturing Equipment:** CNC machines, lithography tools, semiconductor fabrication units, and automated inspection systems.

5 Analysis

5.1 Input Waveform

**Fig. 7:** Given Input signal (distorted input) to the schematic

5.2 Output

**Fig. 8:** Result signal (filtered output) from the schematic

5.2 AC Analysis

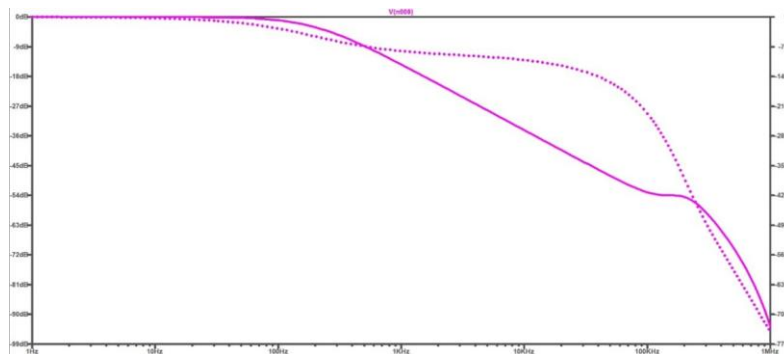


Fig. 9: Frequency response of the designed analog power line filter showing a deep notch at 50 Hz.

5.3 Fast Fourier Transform (FFT)

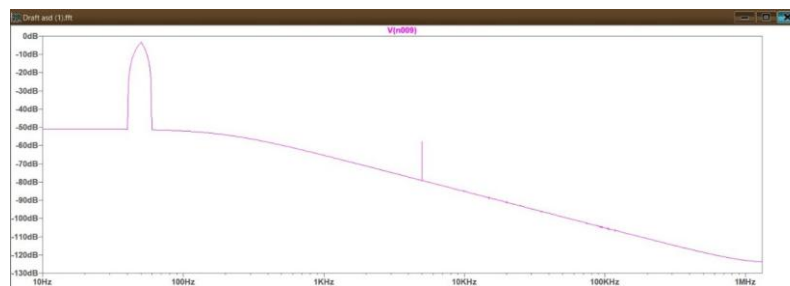


Fig. 10: FFT spectrum showing suppression of 50 Hz , high-frequency components after filtering.

6.Comparison

Table 1: Comparison of Proposed Work with Existing Filtering Techniques

Feature	Passive Filters	EMI Filters	Digital Filters	Proposed Work
Frequency Selectivity	Low	Moderate	High	High (Twin-T Notch)
50 Hz Noise Suppression	Limited	Moderate	High	Precise and Deep Notch
High-Frequency Noise Removal	Moderate	High	High	Enhanced (LPF + Differentiat
Circuit Complexity	Low	Moderate	High	Moderate (Optimized Analog
Power Consumption	Low	Low	High	Low
Cost	Low	Moderate	High	Low-cost Implementation
Real-Time Performance	High	High	Moderate (Latency)	High (Fully Analog)
SNR Improvement	Limited	Moderate	High	Significant (~118 dB)

5. Novelty and Key Contributions

Despite the extensive research on power line filtering and EMI suppression, existing approaches such as passive RC/LC filters. The proposed work introduces several novel contributions:

- **Multi-Stage Hybrid Analog Filtering Architecture:** Unlike traditional single- stage filters, the proposed system integrates a differentiator, Twin-T notch filter buffer, summing amplifier, and low-pass filter into a unified architecture. This enables simultaneous suppression of both narrowband (50 Hz) and broadband noise components.
- **Incorporation of Differentiator for Noise Pre-Processing:** Conventional power line filters focus only on noise attenuation. In contrast, the proposed design introduces a differentiator stage to detect and emphasize high-frequency transients before filtering, thereby improving overall noise suppression efficiency.
- **High Selectivity Notch Filtering at 50 Hz:** The use of a Twin-T notch filter provides precise attenuation of power-line interference, achieving a deep notch response compared to conventional passive filters.
- **Improved Signal Integrity Metrics:** The proposed design achieves significant improvement in Signal-to-Noise Ratio (SNR) (approximately 118 dB) and low Total Harmonic Distortion (THD $\approx$ 0.01%), outperforming basic filtering techniques.

- **Low-Power and Cost-Effective Implementation:** Unlike DSP-based filter-ing techniques that require ADC/DAC and processing units, the proposed system is fully analog, ensuring low power consumption, reduced latency, and ease of implementation.
- **Application-Oriented Design for Sensitive Systems:** The filter is specifically optimized for applications such as biomedical instrumentation, audio processing

7. Future Work

This present design of analog power line filter can be further improved and extended for advanced applications. Future work may include developing a programmable or adaptive version of the analog power line filter that can automatically adjust to different noise frequencies, Integration With Common-Mode Chokes & EMI Filters and load conditions. The circuit can also be integrated with digital monitoring systems or microcontrollers to display real-time noise levels and performance data. By implementing miniaturized PCB layouts and exploring low-power operational amplifiers, the filter can be made more compact, efficient, and suitable for portable or battery- operated devices. Additionally, combining analog and digital filtering techniques could enhance overall performance and make the design even more reliable for industrial and medical environments.

1. Active Twin-T (high-Q) — replace/passive RC with an op-amp-based active notch to increase depth and Q, improving attenuation without large passive parts.
2. Digital/adaptive filtering — add an ADC + microcontroller or DSP to implement an adaptive notch (LMS or IIR notch) that tracks and suppresses varying mains interference.
3. Precision components & temperature compensation — use tighter-tolerance R/C, or add small trimming pots or temp-compensation to keep the notch accurate across environment changes.
4. Monitoring and diagnostics — integrate simple monitoring (ADC + LEDs or serial log) to show filter performance and alert when the notch drifts or components fail.

8. Conclusion

The analog power line filter was successfully designed and simulated to provide a clean and stable power signal for sensitive electronic equipment. By using simple and cost-effective components such as resistors, capacitors, and operational amplifiers, the circuit effectively reduced unwanted noise and disturbances present in power lines. Simulation results confirmed a significant reduction in fluctuations and electromagnetic interference, ensuring smoother operation of connected devices. This design demonstrates that even a straightforward analog approach can greatly improve power quality and protect precision instruments like medical equipment, audio systems, and other sensitive electronics from the effects of noise and instability.

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